BURNING VELOCITY MEASUREMENTS IN ALUMINUM -AIR SUSPENSIONS USING BUNSEN-TYPE DUST FLAMES.

John Lee, Samuel Goroshin, Massimiliano Kolbe
McGill University, Montreal, Quebec, Canada

Introduction.

Laminar burning velocity (sometimes also referred in literature as fundamental or normal flame propagation speed) is probably the most important combustion characteristic of the premixed combustible mixture. The majority of experimental data on burning velocities in gaseous mixtures was obtained with the help of the Bunsen conical flame [1]. The Bunsen cone method was found to be sufficiently accurate for gaseous mixtures with burning velocities higher than 10-15 cm/s at normal pressure [1,2]. Hans Cassel [3] was the first to demonstrate that suspensions of micron-size solid fuel particles in a gaseous oxidizer can also form self-sustained Bunsen flames. He was able to stabilize Bunsen flames in a number of suspensions of different nonvolatile solid fuels (aluminum, carbon, and boron). Using the Bunsen cone method he estimated burning velocities in the premixed aluminum-air mixtures (particle size less than 10 microns) to be in the range of 30-40 cm/s. Cassel also found, that the burning velocity in dust clouds is a function of the burner diameter [4]. In our recent work [5], we have used the Bunsen cone method to investigate dependence of burning velocity on dust concentration in fuel-rich aluminum dust clouds. Burning velocities in stoichiometric and fuel-rich aluminum dust suspensions with average particle sizes of about 5 microns were found to be in the range of 20-25 cm/s and largely independent on dust concentration. These results raise the question to what degree burning velocities derived from Bunsen flame specifically and other dust flame configurations in general, are indeed fundamental characteristics of the mixture and to what degree are they apparatus dependent. Dust flames in comparison to gas combustion, are thicker, may be influenced by radiation heat transfer in the flame front, respond differently to heat losses [6], and are fundamentally influenced by the particular flow configuration due to the particles inertia. Since characteristic spatial scales of dust flames are larger, one can expect that they will also be more sensitive than homogeneous combustion to a particular experimental geometric configuration of the flame and the flow. With such sensitivity the introduction of the very concept of the fundamental flame speed may be problematic for dust combustion. With this in mind, the objective of the present work is to further investigate Bunsen dust flames and evaluate to what degree burning velocities derived from Bunsen cone depend on experimental conditions (i.e. flow rate and nozzle diameter).

Experimental Details.

Dust Burner.

The details of the experimental set-up and principles employed in the dust dispersion system are described in our previous works [5,6]. The following description only specifies modifications that were made to the apparatus in accordance with the objectives of the present work. A simple conical nozzle replaced the water-cooled detached ring that was used previously to stabilize dust flames [5]. The use of the flame stabilized directly on the nozzle, instead of the detached ring, eliminates the uncertainty in flow rate that might result from gas entrainment into the flame from the surrounding atmosphere. With the flame anchored on the nozzle the dust concentration is monitored directly within the dust supply tube by the redesigned laser light extinctiometer. In this modified design, the light emitted by the 3 mW laser diode is introduced into the dust tube through the airflow protected windows, it then passes through narrow channel and is focused by a long focal lens on a small aperture (d= 0.25 mm). The aperture plays the role of a spatial filter that cuts scattered laser light thus making deviation from the Bouguer's light attenuation law negligible even for optically thick dust clouds. A narrow bandwidth interference filter permits only the laser light to pass, protecting the photodetector from the light emitted by the flame and scattered by aluminum particles.

The gas dispersing flow is maintained constant throughout the duration of an experiment, and variation of the dust concentration is achieved by varying the dust feeding rate. In order to regulate the dust flow rate through the nozzle, an ejection system is used to eject part of the flow from the main stream into a bypass tube. Pure nitrogen is used as an ejecting gas. Thus the flow removed from the main stream by the ejector can be easily calculated by measuring the concentration of oxygen in the bypass tube. Oxygen concentration in the ejector flow is continuously monitored by an in-line electrolytic oxygen analyzer and is recorded by a computer data acquisition system.

Aluminum powder.

Atomized aluminum powder (Ampal 637, Ampal Inc., NJ) used in these experiments was from the same batch as in our previous works on flame quenching distance measurements [6] and flame speed measurements in rich mixtures [5]. The powder's al uminum content is no less than 99.5% and the aluminum particles are of a spheroidal or nodular shape. Differential distribution of particle sizes in the powder can be found in our previous work [6].

Dust concentration measurements.

The laser light extinctiometer was calibrated by the complete aspiration of dust from the nozzle flow through a set of filters with a vacuum pump for a known time. Dust mass concentration in the flow is then determined by dividing total mass of the aspired dust by the volume of the gas passing through the nozzle during the same time. Mean particle Sauter diameter (d_{32}) in a suspension can be calculated from the data using Bouger's light attenuation law. The calculations indicate an average particle diameter of about 6 ?m (due to diffraction, light attenuation cross section for particles of this size is twice the size of the particle cross section [7]). This value practically coincides with the average Sauter diameter derived from the particle size distribution (d_{32} = 5.8 ?m), which confirms that the particle agglomeration in the dust flow is negligible.

Photographic arrangement.

The flame image was split by a semitransparent mirror and simultaneously recorded by two single-lens Canon reflex cameras through two different narrow bandwidth interference filters. The bandwidth of one filter coincides with the sodium D-line (589 nm) and the bandwidth of the other coincides with the edge of the green band in the AlO molecular spectrum (508 nm). As the sodium concentration in flame remains constant, the maximum intensity in the sodium radiation might be associated with the maximum flame temperature, whereas the appearance of the AlO line indicates the ignition of aluminum particles. The flame images were digitized using a high-resolution slide scanner. The flame shapes and surface areas of the flame inner cones were determined with the help of image processing software.

Experimental Results.

General observations.

A photograph of the stoichiometric aluminum dust flame is shown in Fig. 1 along with a picture of a stoichiometric methane-air flame stabilized on the same nozzle at approximately the same flow rate (about 300 cm^3/s). In comparison to the methane flame, the dust flame appears to be thicker and a bit larger. The flame base of the gas flame slightly overhangs the nozzle's rim, while the diameter of the base of the dust flame is closer to the inner diameter of the nozzle. The base of the dust flame is also lifted by about 2-3 mm above the nozzle exit while the distance from the nozzle to the base of the gas flame is less than 0.5 mm. The tip of the dust flame is more rounded and the inner boundary of the cone is usually better defined in comparison with the defused outer boundary. At very large dust concentrations the tip of the dust flame often opens up. The size of the opening is however relatively small (1-2 mm). Comparison of the inner flame cone contours derived from the photos taken through 508 nm and 589 nm filters show that they practically coincide with the exception of a small region close to the tip of the flame. The burning velocities derived from these pictures differ by less than 5%; thus only flames filmed through the 508 nm filter were used to measure burning velocity.

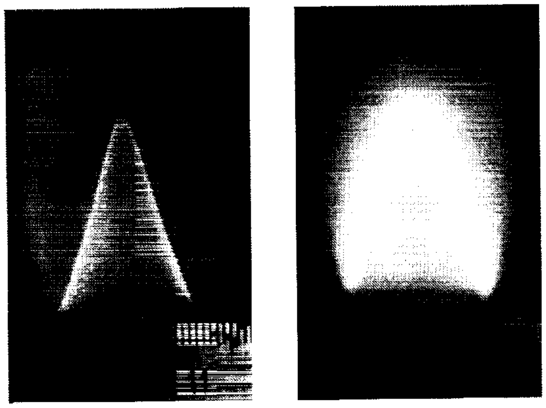


Figure 1. Photographs of the methane-air and aluminum-air stoichiometric flames stabilized on the same nozzle.

Burning Velocity Measurements.

Conical cylindrical brass nozzles with exit diameters 14, 18, and 22 mm were used to stabilize aluminum dust flames at different flow rates. All nozzles have the same base diameter (24.5 mm) and height (60 mm). The dependence of the burning velocity on dust concentration at two different flow rates is shown in Fig. 2 for 18 mm nozzle.

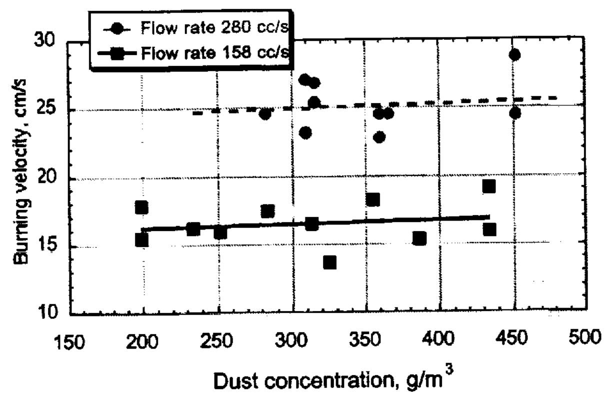
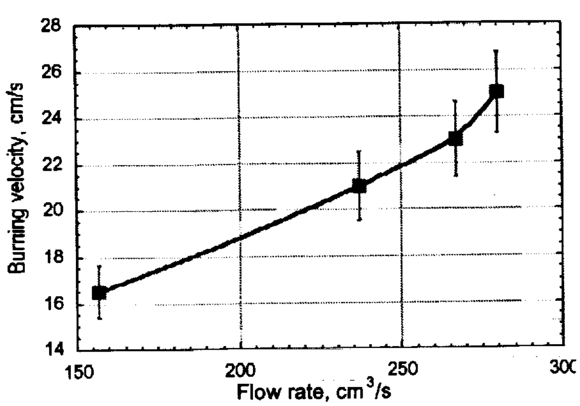


Figure 2. Dependence of burning velocity on dust concentration at two different flow rates (18 mm nozzle).

The derived dependence of the burning velocity on flow rate at approximately uniform dust concentration (350 g/m^3) is shown in Fig. 3. Maximum flow rate at which flame ceases to be completely anchored at the nozzle exit prior to blowoff, is about 300 cm^3/s, whereas at flow rate below 150 cm^3/s the flame is prone to flashback for the 18-mm nozzle.



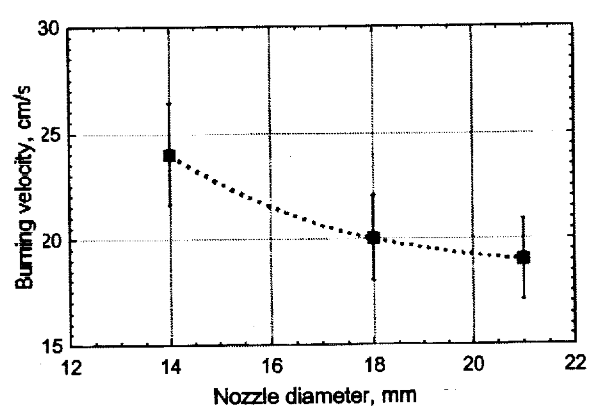


Figure 3. Dependence of the burning velocity on flow rate (18 mm nozzle, dust concentration is about 350 g/m^3).
Figure 4. Dependence of the burning velocity on the nozzle diameter.

The present experiments confirm the result of our previous work [5] which shows that flame speed in rich aluminum suspensions is insensitive to dust concentration. Surprisingly, the burning velocity demonstrates also no noticeable decline in the range of dust concentrations below stoichiometry (200-300 g/m^3). The burning velocity shows clear tendency to increase with the increase in flow rate. In our experiments with different nozzle diameters, we were unable to stabilize flames on the large nozzle (22 mm) at the same flow rates as on 14 and 18 mm nozzles. Thus for the data shown in Fig. 4, the flow rates for two nozzles (14 mm and 18 mm) are the same (~ 280 cm^3/s) whereas for the 22 mm nozzle the flow rate is higher (~ 400 cm^3/s). Nevertheless, the results clearly show that burning velocity decreases with increase in the nozzle diameter. As was mentioned earlier, Cassel reported the same observation in his pioneering experiments with Bunsen dust flames [4].

Discussion.

Radiation effects, with their large characteristic spatial scales, which might be the reason for the strong sensitivity of the dust flame to geometric factor, can apparently be ruled out in explanation of the present experimental results. First of all, the absorption of radiation by a fresh dust mixture is negligible due to the small scale of the investigated flames. Direct measurement of the gas temperature ahead of the Bunsen flame front in our previous work [8], shows no substantial heating of the dust mixture beyond the usual preheat zone maintained by molecular heat conduction. The heat losses caused by radiation emitted by the combustion zone, regardless how substantial they might be, can only lead to decrease in the flame speed for flames stabilized on smaller nozzles or at larger flow rates as they are larger for smaller nozzles and for taller flames.

Cassel suggested [4] that the increase in the burning velocity for dust flames stabilized on smaller nozzles might be the result of the converging heat flux produced by flame curvature analogous to the known effect that increases the flame speed at the tip of the Bunsen gas flame [1]. He speculated that due to the larger thickness of a dust flame (?) the dust burning velocity might be effected even by relatively small (compared to gas) flame curvature as the curvature effect is proportional to $(1+\ ?\ /R)$ (where R is the radius of the flame). The curvature effect can not however explain the observed dependence of burning velocity on flow rate. In addition, our estimations show that the thickness of an aluminum dust flame is actually comparable to the thickness of the methane-air flame. Indeed, the quenching distance for the stoichiometric aluminum flame (measured with the same aluminum powder as in the present experiments) is about 5 mm compared with the methane-air flame which is about 2.5 mm [6]. Relatively small thickness of the aluminum flame can also explain why profiles of the flame cones formed by the sodium and AlO radiation appeared to be very similar. Thus it seems that other effects such as heat losses and (or) peculiarities of the two-phase flow dynamics might be responsible for the dependence of the burning velocity on flame scales observed in the present work.

***Acknowledgment**: This work is supported by the Canadian Space Agency under the Microgravity Science Program and by NASA under the CSA-NASA cooperation program.*

References.

1. B. Lewis and G. von Elbe, *Combustion and explosion of Gases*, Academic Press, NY, 1987.
2. Andrews, G.E., and Bradley, D., *Comb. Flame* 18: 133-153, 1972.
3. Cassel, H. M., Das Gupta, A.K., Guruswamy, S., *Proc. Comb. Inst.* 3: 185-190, 1949.
4. Cassel, H.M., *Some Fundamental Aspects of Dust Flames*, Report of Investigation No. 6551, US Bureau of Mines, 1964.
5. Goroshin, S., Fomenko, I., and Lee, J.H.S., *Proc. Comb. Inst.* 26: 1961-1967, 1996.
6. Goroshin, S., Bidabadi, M., and Lee, G.H.S., *Comb. Flame* 105: 147-160, 1996.
7. Reist, P., *Aerosol Science and Technology*, McGraw-Hill, New York, 1993.
8. Goroshin, S., Shoshin, Yu., Ageyev, N., Poletayev, N., "The Structure of Premixed Aluminum Dust Flame", *Flame Structure*, V. 1, 213-218, Nauka, Novosibirsk, 1991.